Urban Climate 24 (2018) 1011–1026

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Urban Heat Island studies in South Asia: A critical review

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ARTICLE INFO

Keywords:
Urban Heat Islands
South Asia
Critical review
Cities
Tropical Climate

ABSTRACT

South Asian cities are home to nearly 15% of the world's urban population. These cities are experiencing rampant environmental deterioration, making them vulnerable to the impacts of climate change phenomenon, one of which is urban-rural temperature difference known as urban heat island (UHI) effect. While South Asian UHI research publications have tripled since 2000, a comprehensive overview of the experimental results, significant advancements and predominant directions in research is necessary to add clarity to the scientific understanding of tropical and subtropical urban climates and also, to aid city planning and policy-making. A review of 85 original research publications from peer-reviewed journals and conference proceedings in last five decades, covering 28 representative South Asian cities, revealed that Delhi, Chennai and Colombo were most frequently studied and satellite imagery based thermal mapping was used predominantly. Results from few significant studies have shown practical implications for energy use and management, human health, comfort and productivity, reducing air pollution and urban land-use planning. With similar patterns of urbanization, geographies and climate types prevailing across international borders, cities in South Asian region could mutually benefit from collaborative multi-disciplinary research efforts and knowledge sharing to competently respond to and manage the detrimental impacts of urban heat islands.

1. Introduction

As urban populations expand unchecked and per capita incomes grow rapidly, the demand for basic urban amenities like housing, energy, transport, water, waste disposal and sanitation are increasing exponentially (UNEP; SAARC, 2009; World Bank Group, 2015). With climate change at bay, urban growth and resource management is a major challenge to the rising economies, especially in the developing countries. South Asia, defined geographically as the region of Asia that includes Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka, holds 1.6 billion people, almost one quarter of the world's current population. Recent population projections suggest that by 2050, the population of South Asia will approximate or exceed 2.2 billion people (International Institute for Applied Systems Analysis, 2012).

South Asian regions are facing urban sustainability challenges on two front - existing and upcoming. Existing urban challenges includes poverty, rising GHG emissions, pollution concentrations and growing energy demands. South Asia is home to 45% of the world's poor people, living at or below $2 a day (Sumner, 2012), making it more vulnerable to climate impacts. Greenhouse gas (GHG) emissions have doubled in India and Pakistan between 1990 and 2012, with urban areas responsible for over 60% of the increase (The World Bank, 2017, 2010). 11 out of top 20 cities with highest concentration of pollutant ($PM_{2.5}$) belongs to South Asia region (World Health Organization, 2017). Energy consumption of this region went up to 64% between 1994 & 2002 (Lahiri-Dutt,

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https://doi.org/10.1016/j.uclim.2017.12.006
Received 6 July 2017; Received in revised form 26 October 2017; Accepted 18 December 2017
2212-0955/ © 2017 Published by Elsevier B.V.

2006). The upcoming challenges include mitigating the very likely increase in winter temperatures as well as frequency of extremely hot days and nights during the summer (IPCC, 2013). Chan et al. (2012) studied excess mortalities in cities such as Hong Kong, Bangkok, and Delhi and its findings suggest that mortality increases from 4.1% to 5.8% per 1 °C over a temperature threshold of approximately 29 °C.

Faced with the intimidating prospect of irreversible climate change and rampant environmental deterioration, scientific enquiry into the effects of anthropogenic activities and land-use change on urban climate can potentially uncover extensive practical implications for energy use and management, human health, comfort and productivity, urban ecology, reducing air pollution and therefore, a more sustainable urban development (Grimmond et al., 2010; Roth, 2013).

Urban Heat Island (UHI) effect can be described as temperatures observations in towns and cities that are generally higher than in surrounding rural or suburban areas (Oke, 1982). It is also a mechanism that is associated with urban climate impact. UHIs have been proved to occur as a result of the introduction of artificial surfaces, such as buildings and roads made of dry and impervious construction materials, along with human activities that radically alter the energy balance in cities and the atmospheric layers above (Erell et al., 2011; Oke, 1973; Roth, 2013). It exacerbate impacts by affecting rainfall patterns (Collier, 2006), interacting with and worsening air pollution (Xu et al., 2014), increasing flood risk and decreasing water quality (Hester and Bauman, 2013). However, the most direct impact of the UHI on human health is through exposure to increased temperature, which can be particularly problematic during heat waves. The current paper addresses the urban heat island (UHI) effect, which is perhaps the most palpable local climate change phenomenon in tropical and sub-tropical cities.

Due to the bio-physical nature of cities and the multi-layered structure of the atmosphere above them, four distinct types of heat islands have been identified at the micro, local and *meso* scales (Erell et al., 2011; Roth, 2013). At the micro-scale (1–100s m), subsurface and surface heat islands are primarily observed in the daytime and have been observed to affect the temperature of storm water runoff, groundwater characteristics, health of aquatic ecosystems and carbon exchange between soil and atmosphere (Roth, 2013). Studies of the canopy-layer of the atmosphere, found below the tops of buildings and trees, at the local scale (1- < 10 km) have reported the presence of “cool islands” due to shading from tall buildings during the day accompanied by a reciprocal heat island a few hours after sunset (Chow and Roth, 2006; Oke, 1988; Roth, 2013). Apart from affecting the thermal comfort of urban dwellers, the canopy-layer UHI has wide-ranging impacts on building energy use, water use for irrigation, thermal circulation, air quality and urban ecology (Roth, 2013). In the urban boundary-layer, that extends tens of kilometers above the tops of buildings, only weak heat islands that decrease as one moves further away from the city have been reported (Roth, 2013). However, the boundary-layer UHI can still potentially affect regional climate patterns, local circulation, precipitation, thunderstorm activity downwind and plant growing season (Roth, 2013).

Depending on the type and scale of heat island to be studied, various observational and modeling approaches have been adopted to study UHI. Spatio-temporal changes in surface temperature are best captured by the thermal scanners on aircrafts and satellites while fixed weather stations and automobile traverse surveys have been used to record ambient air temperature in the atmosphere (Arnfield, 2003; Mirzaei and Haghighat, 2010; Roth, 2013; Runnalls and Oke, 2000). Physical, statistical and numerical meteorological models have been developed to simulate the energy balance of urban areas and predict weather patterns at varying resolutions (Arnfield, 2003; Roth, 2013).

Since urban heat islands are a global phenomenon, their examination has increased exponentially in the past few decades, reflected in the remarkably rapid growth of available literature on the subject (Arnfield, 2003). However, inquiry into the thermal environment of low-latitude cities in the tropics and sub-tropics had been missing from mainstream UHI research until as recent as the 1950s (Roth, 2013) and therefore, only a handful of studies from South Asian cities were accounted for in previous reviews of UHI literature (Table 1).

Despite the modicum of South Asian UHI studies listed in past reviews, a simple web search of online databases pulls up over a hundred publications, indicating that a substantial amount of research is indeed underway in the region. At this stage, a comprehensive overview of the experimental results, significant advancements and predominant directions in South Asian UHI research is necessary to add clarity to the scientific understanding of tropical and subtropical urban climates and also, to aid city planning and policy-making. This paper aims to address this lacuna by critically reviewing the existing research on UHI in the South Asian region, systematically assessing their practical implications while also directing the scientific community towards areas in dire need of investigation.

2. Methods

Since the study of UHIs, their causes and effects are still at a nascent stage in the tropics and subtropics (Roth, 2007), it was anticipated that the current body of research focused on South Asia, a region comprised entirely of developing countries, would be relatively few in comparison to the more developed countries along the same latitudes.

The literature review began by retrieving a total of 120 research papers on the topic of UHIs in South Asian cities from numerous international and national scientific databases accessible online. Prior to the review process, strict eligibility criteria were applied and only a representative sample of peer-reviewed original research was retained for further analysis (refer Fig. 1). Research papers that did not satisfy one or more of these criteria were subsequently rejected from the sample.

The primary criteria dictated that only studies from cities and urban agglomerations in South Asian region were included in the sample. The second criteria focused on screening papers based on their source of publication and only original or ‘primary’ research published in international or regional peer-reviewed journals were deemed suitable for this review. An exception was made to include relevant studies presented at editions of the International Conference on Urban Climate (ICUC) and International Conference on

Table 1
South Asian literature in past reviews.

Study	Objectives	Selection criteria	Total studies cited	South Asian studies reviewed
Some aspects of the urban climates in India (Padmanabhamurty, 1984)	Reviews existing knowledge in the field	Urban climate studies in India	21	11
Two Decades Of Urban Climate Research: A Review Of Turbulence, Exchanges Of Energy And Water, And The Urban Heat Island (Arnfield, 2003)	Assesses advances in select urban climate processes; explores literature on the urban temperature field	Studies published in International Journal of Climatology	530	1 (Kumar et al., 2001)
Review of urban climate research in (sub)tropical regions (Roth, 2007)	Improves scientific understanding of urban climates in (sub)tropical areas; Provides data and guidance for climate responsive urban design in cities of the developing world	Only examples of key studies to summarize Urban climate processes in these regions	250	25
A review on the generation, determination and mitigation of Urban Heat Island (Memon et al., 2008)	Reviews available literature on the generation, determination and mitigation of UHI	Aimed at summarizing valuable findings, discussing potential research areas.	70	Nil
A systematic review and scientific critique of methodology in modern urban heat island literature (Stewart, 2011)	Uses nine criteria of experimental design and communication to critically assess methodological quality	Observational heat island studies published between 1950 and 2007.	190	Around 8% of studies reviewed. (approximately 15)
Study of the different approaches used to estimate the urban heat island effect in India (More et al., 2014)	Analyzes the transformation undergone in the process of using different tools to assess the formation of UHI in India	Only studies from India	14	14
Three decades of urban heat islands and mitigation technologies research (Akbari and Kolokotsa, 2016)	Analyzes the evolution of the urban climate change as well as its mitigation technologies; particularly summertime UHI	Studies on heat island mitigation technologies published in the last three decades	56	Nil

Countermeasures to Urban Heat Island (IC2UHI). Editorials, surveys and other literature reviews that used secondary sources did not satisfy this second criteria and were therefore, discarded. While the doctoral theses, dissertations and project reports based on primary sources were identified, they were rejected from the sample if they were not published in peer-reviewed journals. The third criteria for selection was that the research objectives of the study be directed at the empirical measurement of one or more of the four heat island types along with their observation or modeling. The studies that also evaluated the impacts of heat islands or proposed adaptive strategies were reviewed for their practical implications in energy use and management, human health, comfort and productivity, air pollution reduction and mitigation.

Despite the multitude of local languages, specialised scientific research in the South Asian region is published in English and as a result, only English language publications were included in the sample. Previous literature on the subject have noted that the first published study on urban heat islands in South Asian cities was in 1973 and hence, all papers that have met the above eligibility criteria were published in the last 5 decades (1973–2017) (Deosthali, 2000). This review was limited to publications accessible online, therefore studies not freely accessible on the internet and those published only in physical copies of journals were omitted.

3. Results

Post the selection process, a total of 85 publications focused on 28 South Asian cities from India, Pakistan, Bangladesh, Sri Lanka and Nepal were chosen for review. Climate zone characteristics and geography of the urban region have been found to play a significant role in influencing UHI, with factors such as sea breeze showing marked influence on the dispersion of thermal pollution (Maral and Mukhopadhyay, 2015; Sarkar et al., 1998; Simpson et al., 2008). The cities studied were found to be representative of the predominant Koppën climate classifications prevalent in South Asia, namely, Warm Semi-arid (BSh), Tropical Savanna (Aw) and Monsoon (Am) in India and Bangladesh, Warm Desert (BWh) and Warm Semi-arid (BSh) in Pakistan and Equatorial (Af) in Sri Lanka (Peel et al., 2006). While most of the cities under study are either coastal or landlocked cities, a small percentage of hilly cities, such as Pune, Jaipur and Dehradun, have also been the focus of UHI studies (refer Table 2).

3.1. Chronology of UHI studies in South Asia

The literature review revealed that Indian researchers were the frontrunners in the South Asian region, with the first study on UHI in the industrial centers of Mumbai and Pune being reported in 1973 (Deosthali, 2000). The early years of UHI research on South Asia was spearheaded by the researchers and officials at the regional and national offices of the Indian Meteorological Department (IMD) with a number of publications being published in the IMD journal titled ‘Mausam’ (Deosthali, 2000; Kumar et al., 2001; Padmanabhamurty, 1984).

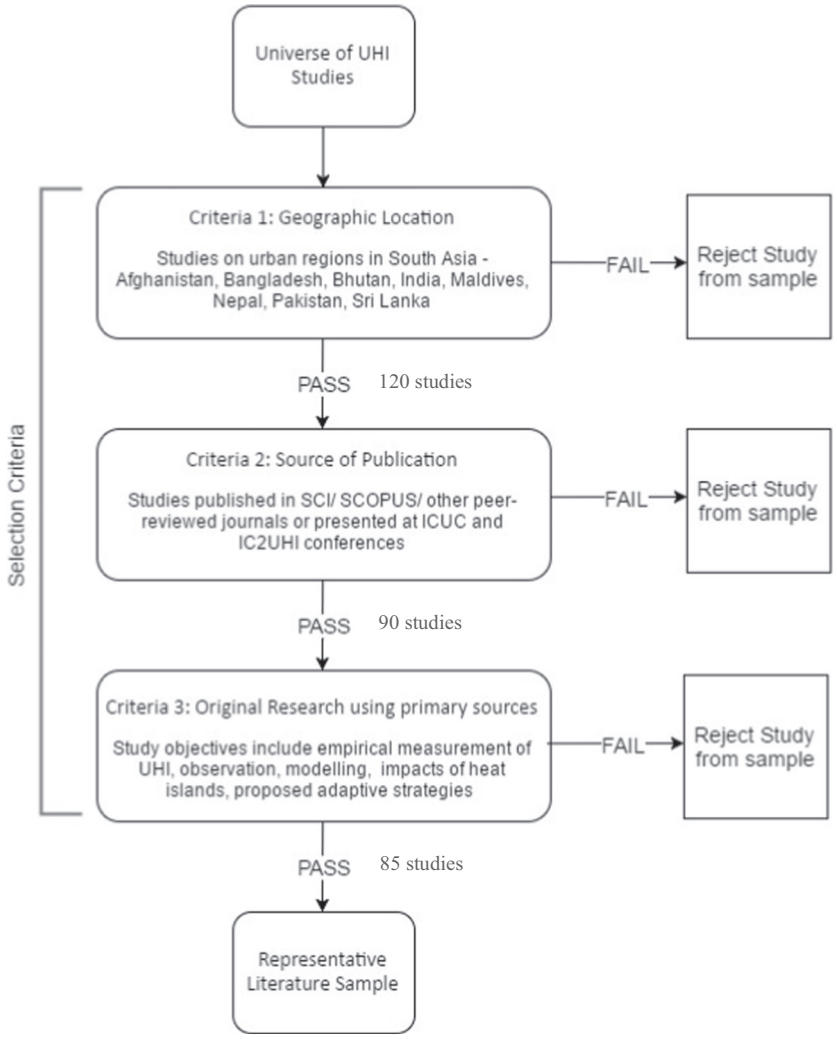

Universe of UHI Studies
Selection Criteria
Criteria 1: Geographic Location
Studies on urban regions in South Asia - Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
FAIL
Reject Study from sample
PASS
120 studies
Criteria 2: Source of Publication
Studies published in SCI/ SCOPUS/ other peer-reviewed journals or presented at ICUC and IC2UHI conferences
FAIL
Reject Study from sample
PASS
90 studies
Criteria 3: Original Research using primary sources
Study objectives include empirical measurement of UHI, observation, modelling, impacts of heat islands, proposed adaptive strategies
FAIL
Reject Study from sample
PASS
85 studies
Representative Literature Sample

Fig. 1. Methodology adopted for selection of studies.

Studies on Indian cities have increased threefold in the last decade (refer Fig. 2) whereas Pakistan which is home to some of the region's most populous cities – Karachi, Lahore and Faisalabad - lags far behind (United Nations, 2016). While in the rest of South Asia, UHI research gained momentum only in the 21st century yet the majority of studies were confined to the national capitals of Dhaka in Bangladesh and Colombo in Sri Lanka. One study each was available for Kathmandu, Nepal and the Pakistani cities of Karachi, Lahore and Sargodha. As of June 2017, no published research on UHI in urban areas of Afghanistan, Bhutan and Maldives were available for review. Primate cities Dhaka and Colombo have been the sole focus of research in Bangladesh and Sri Lanka respectively (refer Fig. 3). With only one available study, the significant absence of Kathmandu, Nepal from mainstream heat island research is unfortunate and must be remedied (Maharjan and Regmi, 2014).

3.2. Source of publications

Only 8% of the representative sample, a total of 7 studies from Chennai, Dhaka and Colombo, were presented at ICUC and IC2UHI conferences, while the remaining publications were from international and regional peer-reviewed journals (refer Fig. 3). 50% of the representative sample were from scientific journals indexed in SCI and SCOPUS, reflecting that a significant amount of noteworthy original research on UHI in South Asia has been undertaken since the turn of the 21st century.

3.3. Methods of observation and modeling

A review of the methods of observation and modeling used to study UHI in the representative sample of publications revealed that over 46% of the studies were based on data collected from satellite observations (refer Fig. 4) from AVHRR, MODIS, ENVISAT AATSR, ASTER and Landsat datasets and therefore, focused on the spatio-temporal variations in surface UHI. Data collected from air

Table 2
Köppen climate and geographical classification of South Asian cities covered in this review.

	City	Country	Köppen Climate[a]	Geography[b]
1	Ahmadabad	India	BSh	Landlocked
2	Bengaluru	India	Aw	Landlocked
3	Bhopal	India	Aw	Landlocked
4	Chandigarh	India	Csa	Hilly
5	Chennai	India	Aw	Coastal
6	Colombo	Sri Lanka	Af	Coastal
7	Dehradun	India	Csa	Hilly
8	Delhi	India	BSh	Landlocked
9	Dhaka	Bangladesh	Aw	Landlocked
10	Dindigul	India	Aw	Landlocked
11	Guwahati	India	Cwa	Hilly
12	Hyderabad	India	BSh	Landlocked
13	Jaipur	India	BSh	Hilly
14	Kanpur	India	Cwa	Landlocked
15	Karachi	Pakistan	BWh	Coastal
16	Kathmandu	Nepal	Cwa	Hilly
17	Kochi	India	Am	Coastal
18	Kolkata	India	Aw	Landlocked
19	Lahore	Pakistan	BSh	Landlocked
20	Mumbai	India	Aw	Coastal
21	Nagpur	India	Aw	Landlocked
22	Noida	India	BSh	Landlocked
23	Pune	India	BSh	Hilly
24	Sargodha	Pakistan	BSh	Landlocked
25	Surat	India	Aw	Coastal
26	Thiruvananthapuram	India	Aw	Coastal
27	Tiruchirapalli	India	Aw	Landlocked
28	Vijayawada	India	Aw	Landlocked

[a] Köppen Climate Types - Af - equatorial, Am - tropical monsoon, Aw- tropical savannah, BSh - semi arid or steppe, Bwh - hot desert, Csa - dry summer or mediterranean, Cwa- humid subtropical.
[b] Geography - Hilly cities defined as those with hills in close vicinity of the urban areas.

temperature sensors from fixed weather stations were used in 31% of the publications, while only 11% used traverse surveys on automobiles to study atmospheric UHI. Meteorological modeling approaches formed a meager 10% of the sample, with the ENVI-Met and WRF being the most commonly used models. Only a single energy balance study from New Delhi was a part of the representative sample.

The dramatic increase in the number of studies using remotely sensed data since 2000, can be attributed to the ease of obtaining presentable results from the satellite images and the abundance of freely accessible satellite data. Availability of remotely sensed data for a particular city is limited to the prescribed time of the satellite's overpass, presence of cloud cover and the viewing geometry of the sensors and therefore, erroneous conclusions are possible if satellite data was not reviewed critically (Roth, 2013). Cities like Jaipur, Ahmadabad, Chandigarh and Bengaluru have been analyzed only using data obtained through satellite images, thus establishing a paucity of field survey campaigns to verify real-world conditions accurately (refer Fig. 4). Atmospheric air temperature observations, either through fixed weather station observations or traverse surveys conducted in select cities have helped understand the three dimensional effects of urban morphology on intra-city near-surface air temperature and wind flow, thus providing

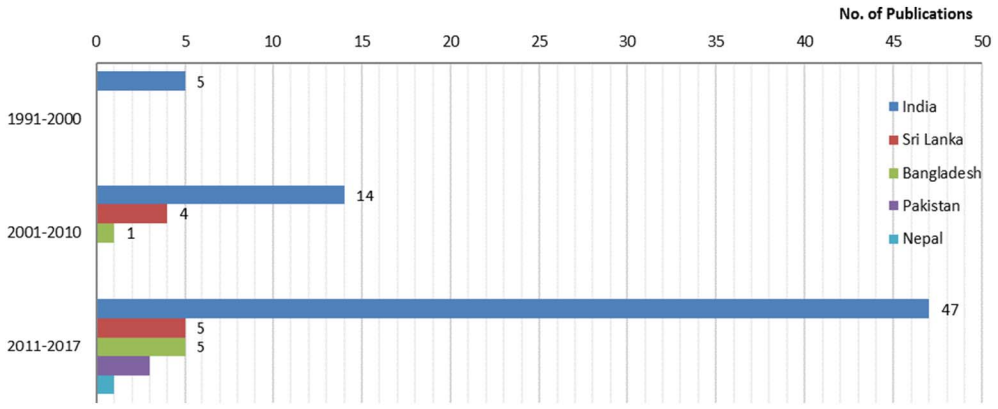


Fig. 2. Decadal increase in UHI studies focused on South Asia.

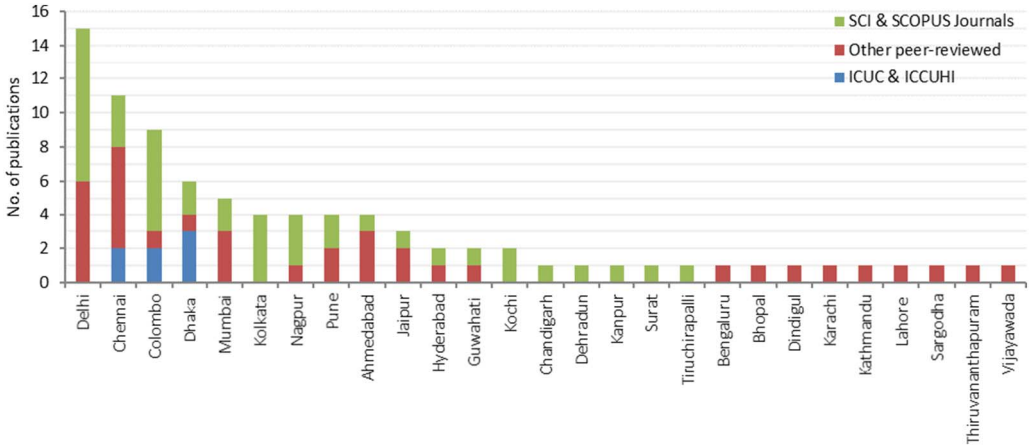


Fig. 3. Source of publication of the representative sample of UHI research on South Asia.

important clues for mitigation strategies focused on urban planning and design (Deosthali, 2000; Kotharkar and Bagade, 2017; Perera and Emmanuel, 2016).

3.4. City-wise summary of existing research

It was surmised that as a result of their rapid urban expansion and their regional as well as national significance, the cities of Delhi, Mumbai and Chennai in India, Dhaka in Bangladesh and Colombo in Sri Lanka, were the focus of over 50% of the papers in the representative sample (refer Fig. 5 Major cities in South Asia's UHI literature and its contribution). The type of UHI quantification studies available for these cities were investigated to find any research gap present. This was based on whether the city covered various scales of UHI (micro, local, regional and boundary layer), extensive data in determining UHI (multiple season or years of used in study), models or simulations and statistical tools (refer Fig. 5 Major cities in South Asia's UHI literature and its contribution). The significant results and major advancements in research from these cities have been summarized below.

3.4.1. Delhi

Fourteen UHI studies from Delhi and one study from its satellite city, Noida were reviewed. Recent studies on Delhi have focused on not only the fluctuations in air temperature but also on the relationship between UHI and air pollution in the city (Pandey et al., 2012, 2009).

Analysis of the historical trends of annual as well as seasonal maximum, mean and minimum temperatures recorded in Delhi over the last century (1906–2005) reported that the significant increase in nighttime temperatures across the city was most likely due to the changes in land-use and the rise in anthropogenic heat. Except for a cool period during the monsoons, the study observed a rise in annual mean minimum temperatures at all stations during the rest of the year (Mohan et al., 2011).

A notable study from 2008, named Delhi Experiments to Learn Heat Island Intensity-I, computes and compares the UHI hotspots in Delhi derived from both in-situ stationary and mobile survey measurements as well as remote sensing data. The most significant

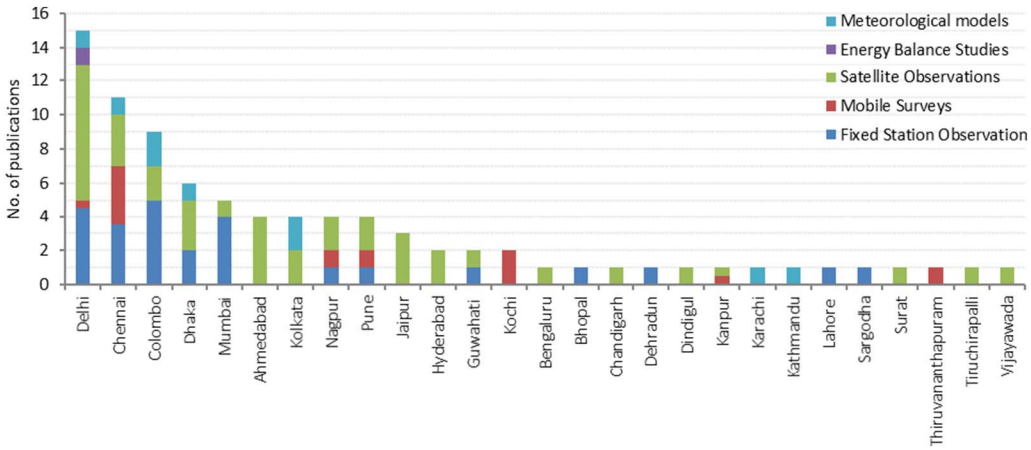
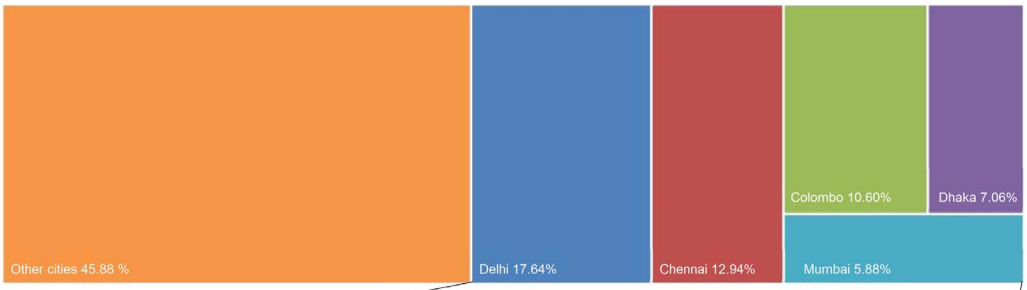


Fig. 4. Methods of observation and modeling approaches used in the representative sample of UHI research on South Asia.



City ID	City	Micro-Scale	Local-Scale	Regional Scale	Boundary Layer Study	Extensive Data	Model/ Simulation	Statistical Method used
1	Delhi	Yes	Yes	Yes	No	Yes	Yes	Yes
2	Chennai	Yes	Yes	Yes	No	Yes	Yes	Yes
3	Colombo	Yes	Yes	Yes	No	Yes	Yes	Yes
4	Dhaka	No	Yes	No	No	Yes	Yes	Yes
5	Mumbai	No	Yes	Yes	No	Yes	Yes	Yes

Fig. 5. Major cities in South Asia's UHI literature and its contribution in UHI quantification.

revelation was that the results of the in-situ temperature measurements and MODIS-Terra data of LST were comparable only during the night (Mohan et al., 2013, 2012).

A year-long study in 2007–08 examined the role of local environment factors in shaping the microclimate of the city with the help of data recovered from automated weather sensors at 13 morphologically different urban locations in Delhi (Roy et al., 2011). Their results stated that the northern and western regions with a high residential densities and industries were the warmest during the daytime, thus placing the physical health of large populations at risk.

A similar study using the temperature data for all twelve months in 2010 from 19 fixed weather stations located across Delhi found that during the day, the warmest temperatures were recorded in the densely populated northeastern, central and southeastern districts of the region while the lowest temperatures were found towards the west and northwest which predominantly consists of cultivated lands (Bhan and Saxena, 2014). The study also noted that the patterns of UHI were similar to those reported three decades ago.

Using observations from Landsat 7 ETM + data, researchers from the Indian Institute of Remote Sensing were able to calculate a statistically significant linear regression equation to predict the land surface temperature from measurements of Normalized Difference Vegetation Index, a value that reflected the vegetation cover in the city (Javed Mallick and Bharath, 2008). Satellite-based ASTER datasets were overlaid with the ward-wise population data from the Census of India 2001 to assess the relationship between the land surface temperature and population density (Mallick and Rahman, 2012). The results of this study showed that areas with higher population densities and therefore, higher impervious surface area ratios were prone to experiencing higher surface temperatures at night.

On analyzing the seasonal variations in spatial patterns of daytime UHIs in Delhi using the Landsat TM data with respect to LU/LC practices it was found that the major commercial and industrial hubs and the airport are the areas at risk with UHI intensities as high 16.7 °C in the summers and 7.4 °C in the winters (Sharma and Joshi, 2014).

Conversely, another study used five Landsat images from different seasons to extract surface temperature patterns and consequently, the north-south and east-west temperature gradients across the city to find that in comparison to the sandy and agricultural lands on its peripheries, the core of the city experienced lower temperatures and weak daytime UHIs due to the presence of the Yamuna River and the thickly vegetated Delhi Ridge in its vicinity (Singh et al., 2014).

The WRF meteorological model used in combination with the urban canopy model by researchers at IIT, Delhi to simulate the air temperature and the surface skin temperature was able to correctly predict the high UHI zones in the city during the day and night times (Bhati and Mohan, 2016). While the simulated UHI zones were more spread out in comparison to the isotherms prepared from the observed data, the model was able to calculate the presence maximum UHI intensities of 5.36 °C at night in the city.

In the only study of energy balance measurements in a suburban vegetated area of southern Delhi, the division of net radiation (Q*) into sensible (H) and latent (LE) heat in summers and winters were calculated and the results provided conclusive evidence of the effect of vegetation in “increasing the LE, decrease of Bowen ratio and consequently higher apportionment of Q* in evaporating the surface moisture” during the winter seasons (Das and Padmanabhamurty, 2008).

3.4.2. Mumbai

Despite being the focal point of the earliest studies conducted in the region, the 21st century has seen only a marginal increase in UHI research concentrated on the city (Padmanabhamurty, 1984). Initial studies conducted in the 1970s identified the beneficial influence of sea breeze on the horizontal temperature distribution in the rapidly urbanizing industrial hub (Kumar et al., 2001;

Padmanabhamurty, 1984). A detailed examination of three decades of maximum and minimum temperatures recorded in the city reiterated this conclusion to state that during the daytime, coastal areas remained cooler than the inner city regions while the opposite occurred at night (Maral and Mukhopadhyay, 2015).

Mobile temperature surveys conducted on one winter and one summer night in the city identified maximum heat island intensities away from the coastal boundary and as high as 11.8 °C in the winter and 5.5 °C in the summer (Kumar et al., 2001). The study also determined that the sub-urban railway routes were the warmest parts of the city and that the effects of urbanization had overtaken the positive influence of sea breeze.

Most recently, the IMD examined the hourly temperature data during the period of 1969–2009 from two observation stations, one in the center of the city and the other at the airport. The study found that the over the last two decades there has been an increased occurrence of a night time temperature difference of at least 3 °C magnitude between the airport and the city center (Srivastava et al., 2016). Similarly, the Regional Meteorological Department investigated trends in maximum and minimum temperatures at different temporal scales from decadal to daily to find an increasing trend with the rise in maximum temperatures more than minimum temperatures (Nair and Hosalikar, 2013). These trends also showed an increased warming in the winter and post-monsoon seasons.

Another recent study used Landsat 5 TM data from 26 October 2010 to map the spatial patterns of LST over Mumbai (Grover and Singh, 2016). The results revealed that the central and southern parts of the city had the highest temperatures while the outskirts showed lower temperatures during the daytime.

3.4.3. Chennai

The earliest study in Chennai was conducted in the early 1990s using air temperature data collected from an 8-day long mobile traverse survey to record variations in temperature (Jayanthi, 1991). Around the same time, surface temperature, humidity and wind data observed at 77 points along a mobile survey route were used to discuss the heat island formation in the city in a separate study by Sundersingh (Sundersingh, 1991). Additionally, Sundersingh compared and studied the three-dimensional structures of the temperature distribution from special radiosonde-radiowind ascents in one urban and one suburban observatory. A range of mitigation measures and suggested areas of future research were also touched upon in his study.

In 2008, observed air temperature data from fixed weather stations as well as traverse surveys were used to explain the relationship between the UHI intensity in the city and various urban factors during the hottest summer month (Rose and Devadas, 2008). The study concluded that the highest UHI intensities of 5.5 °C during the day were observed in the commercial center of the city and therefore, surmised that the presence of vegetation reduced air temperatures in the city and its suburbs. Results from analysis of satellite data by the same team of researchers arrived at a similar conclusion, an increase in building density and the corresponding decrease in open spaces and green cover in the city are the underlying causes of UHIs (Amirtham et al., 2009).

Using observed air temperature from traverse surveys, researchers from the Centre for Climate Change and Adaptation Research, Anna University noted that the densely populated commercial hubs in the central and northern parts of the city were 3–4.5 °C warmer at 0530 h (Jeganathan et al., 2016).

Satellite based observations from Landsat TM were used in another study to examine the prevalence of high temperature in the city and its relationship to the increasing population and decreasing vegetation cover from 1991 to 2006 (Sakthivel et al., 2014). The paper reported that the with the manifold increase in built-up area and resulting decrease in vegetation cover during the study period caused urban areas to be warmer than the surrounding countryside in the daytime.

3.4.4. Dhaka

Dhaka has been predominantly studied using satellite-derived LST, with only one available study using mobile traverse survey method (Rob et al., 2015). Using Landsat data over the period 1989–2009 to derive LST maps, relationships between thermal environment and land use/land cover (LU/LC) in the city were analyzed in order to advise future urban planning strategies for the city (Raja, 2012). The relationship between LU/LC changes and the LST over a period of 21 years was examined for the Ganges-Brahmaputra delta, a densely populated region of high ecological significance to both India and Bangladesh (Chaudhuri and Mishra, 2016). The results found that changes in LST were largely dependent on urban growth and that the mean LST in January decreased by approximately 1.83 °C in the Indian territories and 1.85 °C in the Bangladeshi territories. Remotely sensed data was also used to assess the LST data to understand the intensity and dynamics of heat islands in the city using meteorological observations as well as WRF model simulations (Das et al., 2015). The analysis showed high UHI intensities in the commercial hubs mainly during the night and afternoon hours.

3.4.5. Colombo

Emmanuel has contributed to several studies of the UHIs in Colombo since the 2000s (Emmanuel et al., 2007; Emmanuel and Fernando, 2007; Johansson and Emmanuel, 2006; Perera and Emmanuel, 2016). A 2006 study examined the effects of urban morphology and sea breeze on the microclimate of Colombo. The findings showed that increased shading and opening up wind corridors to sea breeze can help lower the harmful effects of higher ambient air temperatures (Johansson and Emmanuel, 2006). Another study from 2007, used the micro-scale urban simulation program, ENVI-met, to examine the sensitivity of air temperature and mean radiant temperature of the dense urban cores to the density of buildings, albedo of various artificial surfaces and the green cover (Emmanuel et al., 2007; Emmanuel and Fernando, 2007).

Using Landsat-7 ETM + satellite imagery, a study was conducted to identify the spatio-temporal behavior of UHIs and formulate a deductive index to locate the critical areas based on the distribution of LST and the presence of green cover (Senanayake et al., 2013).

The most critical areas in need of future urban planning remedial measures were found to be the Colombo harbor and its surroundings.

3.4.6. Significant studies from other cities

The remaining cities covered in the representative sample of UHI studies were examined through fewer than 5 studies each, with 15 cities examined in only a single publication. A significant amount of UHI research has been carried out in Nagpur and Pune focusing on surface as well as atmospheric UHI intensities measured (Deosthali, 2000; Ganguly and Shankar, 2014; Katpatal et al., 2008; Kotharkar and Surawar, 2016; Nesarikar-Patki and Raykar-Alange, 2012). Recent studies in Ahmadabad using satellite observations to measure surface UHI intensities shown that LULC changes in the city were a major cause for the rise in surface temperatures and that intensities were highest in the afternoons compared to the mornings (Joshi et al., 2015; Mathew et al., 2015; Vyas et al., 2014). Investigations in Kolkata revealed that during the summer months, mean temperatures under the urban concrete surface environments is about 3.54 °C greater than that of adjacent suburban open surface (Khan and Chatterjee, 2016). Satellite observations of the city noted that surface temperatures showed a distinct warming trend from 27.36 °C in 1989 to 30.025 °C in 2006 and 33.023 °C in 2010 (Sharma et al., 2015). A summary of observations of UHIs in these cities is presented below (Table 3).

3.5. UHI impacts

The gap between academic heat island impact research and real-world implementation of adaptation and mitigation strategies is to be bridged, it is necessary to understand the depth of UHI research in the South Asian region. For this purpose, the UHI study composition was reviewed considering how many research articles out of the selected sample presents findings on UHI magnitude, its contributing factors, impacts and mitigation measures (refer Fig. 6). While almost all the studies are oriented towards determining UHI magnitude, only two third of them report the contributing factors. Land use land cover change is mentioned in vast number of remote sensing studies. However, the UHI Impacts and mitigation were not assessed in major proportion of literature. It is important to understand UHI impacts in South Asia prior to proposing any mitigation strategies. The review therefore summarizes the important literature related to impacts concerning energy consumption, health, comfort and environmental impacts.

3.5.1. Energy consumption

Hotter days and nights, particularly in the low-latitude cities, cause intense thermal discomfort and inconvenience to the urban population, thus escalating the energy demand for artificial indoor air cooling (Grimmond et al., 2010; Roth, 2013). UHIs have become a self-fulfilling prophecy as they are both the cause and result of increased energy use in urban areas, creating a vicious circle of energy consumption and generation (U.S. Environmental Protection Agency's Office of Atmospheric Programs, 2008).

Studies focusing on the possible implications of UHI on energy use and management are limited due to the lack of detailed tracking of electricity utilization in South Asian cities to corroborate results. While several studies mention that impact of urban warming on peak energy use, very few studies have been carried out in South Asia to precisely understand the relationship between UHI and energy use in cities. One notable study on Colombo proposed to estimate the impact of urban land-use changes and subsequent heat islands on energy demand (Ukwattage and Dayawansa, 2012). Using satellite imagery, the study calculated that western Colombo, a region forming 15% of the city's extent, was comprised of over three-quarters built up area and only 19% vegetation cover. Following which, the ratio of energy consumed per land area showed that the western region was the highest consumer of electricity with nearly three times as much energy use per hectare as each of the remaining regions.

3.5.2. Human health and comfort

Fluctuations in human comfort levels due to the influence of heat islands has been the focus of researchers across South Asia, with a range of thermal comfort indices like Physiologically Equivalent Temperature (PET), Temperature–Humidity Index (THI) and Relative Strain Index (RSI) used to evaluate outdoor conditions. Emmanuel and Johansson measure the environmental parameters affecting thermal comfort and estimated it by calculating PET values (Emmanuel, 2005; Emmanuel et al., 2007; Johansson and Emmanuel, 2006). The thermal discomfort was found to be high due to the combination of intense solar radiation, high temperatures, and low wind speeds, especially on clear days. The worst conditions were found in wide streets with low-rise buildings and no shade trees. The most comfortable conditions were found in narrow streets with tall buildings, especially if shade trees were present, as well as in areas near the coast where the sea breeze had a positive effect. Their research also suggested mitigation measures, such as a more compact urban form with deeper street canyons, tree-covered walkways, pedestrian arcades, etc.

One study presented an analysis of human comfort in the Chennai Metropolitan Area in terms of the THI, that includes the effects of air temperature, and RSI, that accounts for the effects of clothing and net radiation (Lilly Rose, 2010). Using the historic climate records for the past two decades, the study confirmed that due to the existence of a UHI in the city, 100% of the people would feel uncomfortably hot during the day as per THI and 75% would be distressed as per RSI.

A study on the impact of urbanization on heat and moisture islands in the city of Pune found that the coexistence of heat and moisture islands tends to reduce night comfort in cities from Deccan Plateau during the warm, dry season (Deosthali, 2000, 1999). Using THI, the study concluded that during office working hours (08:30–17:30 h), the city experienced varying levels of discomfort during eight months of the year (Deosthali, 1999).

Table 3
Methods and results from selected UHI studies from cities in South Asia.

Study	City	Estimated population[a]	Koppën climate type	Duration of study	Method of study	Results
(Mathew et al., 2016a, 2016b)	Ahmadabad	7,796,383	BSh	2004–2013 (10 years)	Satellite-derived LST	Overall average UHI intensity January, March and May has been observed to be 7.13 K, 8.38 K, and 4.09 K, respectively.
(Ramachandra and Uttam, 2009)	Bangalore	10,818,727	Aw	1973–2007 (34 years)	Satellite-derived LST	Increase in paved surfaces by 466% led to increase in LST by 2 °C in last 20 years
(Mathew et al., 2016a)	Chandigarh	1,055,450	Csa	2009–2013 (5 years)	Satellite-derived LST	Overall average UHI intensity during monsoon, summer and winter seasons is 4.65 K, 5.92 K, and 5.03 K, respectively; central part hotter than surroundings.
(Singh et al., 2013)	Dehradun	569,578	Csa	1967–2007 (40 years)	Fixed weather stations	During 1988–2007, annual maximum, annual minimum and annual mean temperatures increased about 0.42 °C, 0.59 °C and 0.54 °C, respectively.
(Rajeshwari and Mani, 2014)	Dindigul	207,327	Aw	24th March 2014	Satellite-derived LST	Highest LST of 324 K observed in barren lands, wastelands in northern region. Elevated regions with dense vegetation showed lowest LST < 305 K
(Borbora and Das, 2014)	Guwahati	1,076,799	Cwa	1st May – 17th October 2009 (170 days), June–August 2009 (mobile traverse)	Fixed weather stations and mobile traverse survey	Night-time temperature difference from June–August ranged from 1.23 to 0.78 °C. Summertime UHI intensity frequently above 2 °C.
(Badarinath et al., 2005)	Hyderabad	9,489,467	BSh	6th–7th March 2003 (2 days)	Satellite-derived LST. Both day and night images used.	Lower LST over water surfaces (18–21 °C). Maximum LST over urban areas (36–40 °C)
(Jalan and Sharma, 2014)	Jaipur	3,638,277	BSh	2001–2009	Satellite-derived LST	Average increase of 2.99 °C in overall summer temperature. New suburbs of the city record 2–4 °C increase in LST.
(Chakraborty et al., 2017)	Kanpur	3,073,507	Cwa	April–September 2014	Fixed weather stations	Canopy Layer UHI intensity higher during pre-monsoon nights (3.6 °C) than monsoon nights (2 °C). Surface Layer UHI higher during monsoon (5 °C) than pre-monsoon (3.4 °C).
(Sajjad et al., 2015a)	Karachi	17,635,848	BWh	19th–22nd April 2005 (3 days)	Meteorological modeling	Maximum UHI intensity at 21:00 h was 13.5 °C
(Maharjan and Regmi, 2014)	Kathmandu	1,266,114	Cwa	1 year (2012)	Meteorological Modeling	UHI intensity of 2 °C over the northwestern central area of Kathmandu in summer and winter
(Thomas et al., 2014)	Kochi	2,553,013	Am	November 2007 – March 2013	Fixed weather stations and mobile traverse survey	Winter UHI at pre-dawn and early night was 4.6 °C and 3.7 °C respectively. Max. UHI intensity during summer morning was 3.7 °C
(Khan and Chatterjee, 2016)	Kolkata	15,119,354	Aw	June 2015 (30 days)	Meteorological modeling	Maximum UHI intensity is 3.54 °C. RH in urban areas was 79.52% lower during morning and afternoon.
(Sajjad et al., 2015b)	Lahore	9,244,985	BSh	1972–2011 (39 years)	Fixed weather stations	Urban station showed 3.24 °C increase in Winter and Spring temperature over 40 years
(Kotharkar and Surawar, 2016)	Nagpur	2,758,581	Aw	22nd March, 4th April, 26th April, 16th May, 30th May, 7th June in 2012, 17th January, 24th November, 11th January in 2013, 11th January, 13th January, 8th February in 2014. (12 days)	Mobile temperature survey	Nocturnal mean canopy UHI intensity was 2.14 °C during summer and 2.36 °C during winter traverse surveys
(Deosthali, 2000)	Pune	6,037,229	BSh	12th–13th April 1997 (2 days)	Mobile temperature survey	UHI intensity increases from 2 at 20:00 h to 3.1 °C at 05:00 h before sunrise

(*continued on next page*)

Table 3 (*continued*)

Study	City	Estimated population[a]	Koppën climate type	Duration of study	Method of study	Results
(Sajjad et al., 2015c)	Sargodha	2,665,979	BSh	19th–22nd September 2014 (4 days)	Fixed weather stations	Highest UHI intensity between urban and rural stations was found to be 5.7 °C on a Sunday evening.
(Muthamilselvan et al., 2016)	Srirangam, Tiruchirapalli	847,387	Aw	2001–2013 (13 years)	Satellite-derived LST	Surface temperatures increased by 1.1 °C over 13 years. LST varies from 24.7 to 35.9 °C for 2013.
(Sharma et al., 2013)	Surat	6,149,494	Aw	19th October 1990, 23rd October 2009 (2 days, 19 year difference)	Satellite-derived LST	LU/LC changes from vegetation to built-up resulted in 5.5 ± 2.6 °C increase in LST, vegetation to fallow 6.7 ± 3 °C, fallow to built-up is 3.5 ± 2.9 °C and built-up to dense built-up is 5.3 ± 2.8 °C
(Ansar et al., 2012)	Thiruvananthapura-m	743,691	Aw	29th June 2010	Mobile temperature survey	Maximum nocturnal UHI intensity at city center was 2.4 °C. Peak nocturnal cooling rates at rural area was 3.4 °C/h
(Kumar et al., 2012)	Vijayawada	1,884,334	Aw	31st October 2010 (1 day)	Satellite-derived LST	Highest LST at urban built-up areas 320 K. Lowest LST of 299 K in vegetated areas.

[a] Population data sources: India - Census of India 2011, Pakistan - Asian Development Bank, Sri Lanka - Department of Census and Statistics, Sri Lanka, Bangladesh - Bangladesh Bureau of Statistics Population and Housing Census 2011.

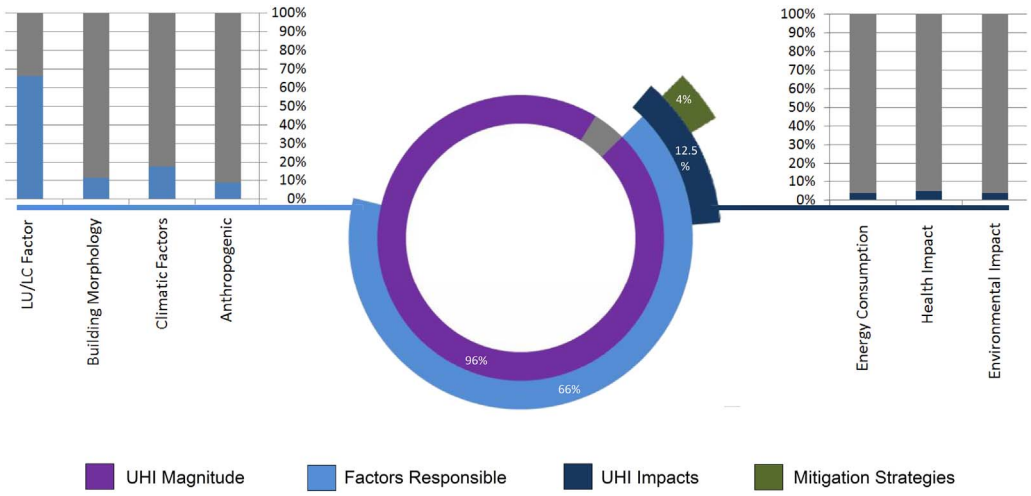


Fig. 6. UHI research composition showing study percentage out of selected sample that are focused on determining UHI Magnitude, factors responsible, impacts and mitigation.

3.5.3. Environmental degradation

High levels of pollution in and around cities are known to increase UHI by modifying the radiative properties of the atmosphere (Grimmond et al., 2010; Roth, 2013). Delhi, being a densely populated, landlocked mega-city, battles considerable air pollution throughout the year (Sharma and Dikshit, 2016). One study mapped the thermal environment of the city and compared it to the value of aerosol optical depth (AOD) (Pandey et al., 2009). During summer days, it was observed that regions with high AOD values generally tended to have lower temperatures than regions with lower AOD values. The study concluded that the aerosol distribution and the presence of a major water body (river Yamuna) appeared to be the contributing factors to the observed distribution of surface temperature during the daytime. However, during summer nights, a distinct UHI formation was observed in the central parts of Delhi in all the summer months. It was concluded that this temperature elevation of 4–7 °C in the urban areas over the rural areas in almost all the months added greatly to human discomfort in the city, leading to increased load on air conditioning, thus increasing the electricity consumption appreciably.

A similar study conducted in Delhi during the winter months revealed a strong anti-correlation between wind speed and particulate matter concentration (Pandey et al., 2012). The high values of particulate matter present during low wind conditions were found to help the formation of daytime “cool islands” of 4–6 °C over central parts of Delhi. The results suggested that the anthropogenic centers of urban Delhi behave like moderators of temperature variations in low wind conditions.

3.6. Investigations for mitigation strategies

Researchers from assorted scientific disciplines have joined the effort, employing a variety of methods from ambient air temperature observations to deriving land surface temperature from remotely-sensed data. UHIs are known to exacerbate extreme heat conditions and therefore, it is surprising that researchers focused on disaster risk and mitigation studies form a very small fragment of the pie.

A study on the city of Dhaka used Landsat satellite images of 1989, 1999, and 2009 to identify patterns of LU/LC changes between the periods and investigated their impacts on LST (Ahmed et al., 2013). Applied artificial neural networks were then used to simulate LU/LC changes for 2019 and 2029; and finally, estimated their impacts on LST in respective periods. Simulation results showed that if the current trend continued, 56% and 87% of the area would likely experience temperatures in the range of greater than or equal to 30 °C in 2019 and 2029, respectively. The findings possess a major challenge for urban planners but would help them to quantify the impacts of consequently to devise appropriate policy measures.

In 2016, a study from Colombo, established the relationship between green cover losses and its impact on thermal comfort by calculating the Temperature-Humidity and Relative Stress indices (Asmone et al., 2016). The study proposed policy recommendations in the form of a conceptual framework for an urban green cover protocol to help mitigate the postulated impacts from the case study. While it was clearly understood that urban development must not be stopped as to protect trees, it is possible to preserve the green cover with the use of controlled development practices. Green construction was not advised to be used as a stand-alone strategy from the urban perspective, but as a supporting role to complement the holistic measures taken to obtain the most benefits out of it.

Emmanuel and Fernando have used ENVI-Met to simulate the sensitivity of air temperature and mean radiant temperature (MRT) of built-up urban cores to the density of buildings, thermal properties of human-made surfaces and green cover in Colombo (Emmanuel and Fernando, 2007). Their study identified that although high albedo values lead to low daytime temperatures, the best thermal comfort, quantified by both the air temperature and MRT, was found in high-density development. They suggested that, from an urban design point of view, mitigation options ought to focus on thermal comfort enhancement (including the MRT) rather than merely attempting to control air temperatures.

Since the proposal of the Local Climate Zone (LCZ) (Stewart and Oke, 2012) as a system of classification of urban areas to enable study UHI, LCZ maps have been published for Colombo, Nagpur and Kochi (Kotharkar and Bagade, 2017; Perera et al., 2012; Perera and Emmanuel, 2016; Thomas et al., 2014) and investigations are underway for several other cities across the region (World Urban Database and Access Portal Tools, 2015). Apart from allowing researchers to generate reliable comparisons of inter-LCZ UHI intensities, this system is a useful tool to accurately ascertain which of the urban factors, such as height of buildings, sky view factor, building surface fraction, etc. must be modified to significantly change the UHI magnitude (Stewart and Oke, 2012). Analysis of predawn and nighttime air temperatures observed through traverse surveys in the 10 different LCZs of Kochi showed that maximum UHI intensities (3.7–4.6 °C) were observed in compact mid-rise zones (LCZ 2), i.e. city regions with densely packed buildings of with three to six floors in height (Thomas et al., 2014). Along with the LCZ maps of Colombo, the research team have suggested that the transformation of LCZ 6 (open low-rise) to LCZ 1 (compact high-rise) can result in a considerable warming of 2.53 °C (Perera and Emmanuel, 2016). The paper also highlighted that a warming of 3.25 °C could occur when the ongoing modification of warehouses (LCZ 8 - large low-rise) into high density developments (LCZ 1 - compact high rise and LCZ 4 - open high-rise) was completed.

4. Discussions and concluding remarks

This review presents a holistic understanding of the most relevant UHI studies conducted in South Asia, significant findings and their practical implications for cities. Majority of the existing research is limited to merely quantifying the UHI phenomenon, while its causes and effects are not explored in depth. In particular, defining the physical structure of a city has been very ambiguous with most papers not providing sufficient description of the characteristics of their 'urban' and 'rural' observation points, thus preventing accurate comparisons of UHI intensity across cities (Stewart, 2011). Several studies across South Asia have rigorously examined certain factors, such as urban LU/LC changes, their respective fluctuations in vegetation cover using various methods to deduce these factor's role in aggravating UHI formation. Satellite-based studies in particular have been conclusive on the strong negative correlation between the presence of vegetation and the formation of UHIs (A. Mathew et al., 2016a, 2016b; Ramachandra and Uttam, 2009; Sharma et al., 2013).

The system of Local Climate Zone mapping has been used to classify urban fabric and rationally analyze the effects of particular physical attributes on UHI formation in Delhi, Colombo, Nagpur and Kochi (Kotharkar and Bagade, 2017; Perera and Emmanuel, 2016; Roy et al., 2011; Thomas et al., 2014). LCZ maps could potentially be utilized to generate optimum land use and building design scenarios that would be economically viable in South Asian cities while also effectively reducing the UHI intensities. Architects and urban planners gain valuable knowledge from the results of UHI studies that correlate aspects of city design to the fluctuations in human thermal comfort (Emmanuel and Johansson, 2006).

While a majority of cities across South Asia have evolved in a similar manner due to their colonial past, the benefits of standardized solutions, such as tree planting, to varying geographical contexts must be evaluated before mandating as UHI mitigation policies. As represented in Fig. 5, only five cities cover > 50% of UHI literature in South Asia. Out of these, three cities lie in coastal region and remaining two are land locked region. Their geographical setting and climate type are different. Thus, extracting unique characteristics of UHI through comparative analysis is difficult. Indigenous and multidisciplinary approach is required for appropriate investigation.

To meet the existing and upcoming challenges related to urban heat island, South Asian cities need to fill the research gap on several aspects as mentioned in this review. Boundary layer UHI study is still unattended in UHI determination for this region (refer Fig. 5). As shown in Fig. 6, important UHI contributing factors such as building arrangement, sky-view factors, aspect ratio and anthropogenic factors are studied only for few cities. Development of statistical regression models for micro and local level UHI research encompassing these factors should be encouraged. The nexus between UHI contributing factors and UHI mitigation strategy is the quantification of UHI impacts. Literature on energy consumption, health and environmental impacts contribute to < 10% of the UHI research. World Health Organization data on ambient air quality indicates that Delhi, Dhaka and other 27 South Asian cities in top 50 most polluted cities of the world (World Health Organization, 2017). Assessment of UHI impacts and effective urban planning is the most crucial strategy to reduce the effects of UHI on public health and urban systems in South Asia.

With similar patterns of urbanization, socio-economic and climate types prevailing across international borders, cities in the South Asian region could mutually benefit from collaborative multi-disciplinary research efforts and knowledge sharing to competently respond to and manage the detrimental impacts of urban heat islands. Periodic regional conferences and workshops can ensure that future research efforts are directed towards closing the gaps in knowledge of UHI in tropical and subtropical urban climates and that a compelling base of conclusive scientific facts is ready at hand to aid governments in envisioning climatologically effective and economically viable city planning solutions.

Acknowledgement

The study is supported by the Department of Science and Technology, Government of India and is funded by Science and Engineering Research Board (DST-SERB project SB/S4/AS-110/2013). We thank the Department of Architecture and Planning, Visvesvaraya National Institute of Technology for providing necessary infrastructure. We would also like to thank the two anonymous reviewers for their comments which added quality to this paper.

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